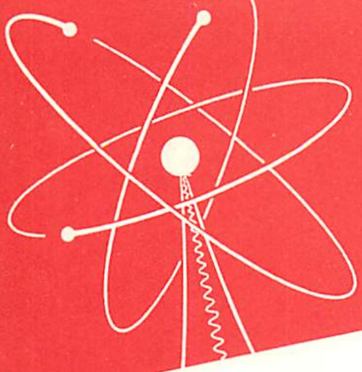

TRANSMISSION LINES

Lesson T2C-19A

DeVRY Technical Institute
4141 W. Belmont Ave., Chicago 41, Illinois
Formerly DeFOREST'S TRAINING, INC.

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T2C-19A

TRANSMISSION LINES

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DeVRY Technical Institute
Chicago 41, Illinois

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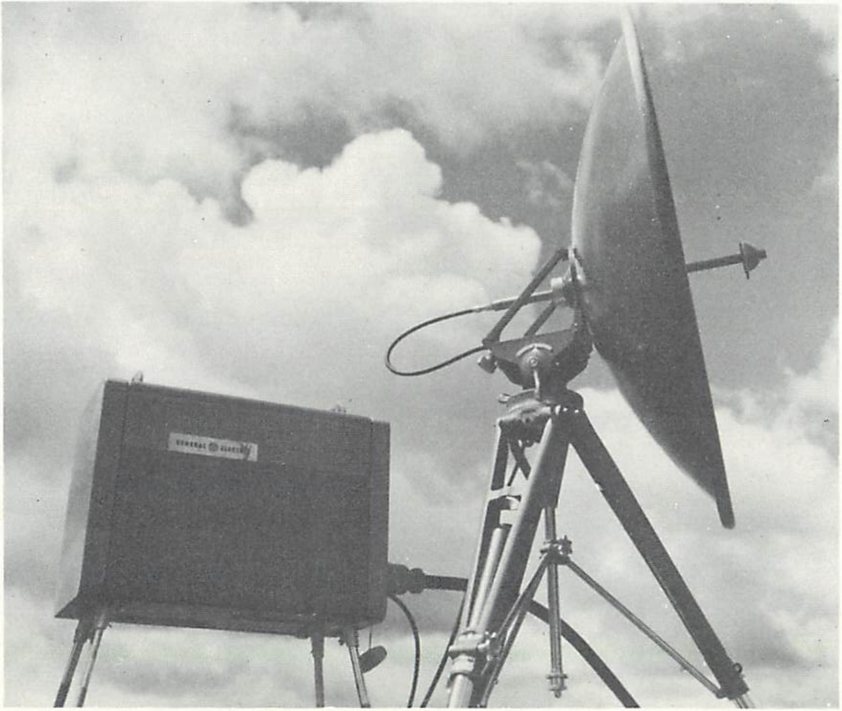

A microwave antenna (parabolic dish) and associated equipment used to beam television programs from remote points to main studios. Coming out of the rear of the reflector is the coaxial transmission line used to supply r-f power from mobile transmitter.

Courtesy General Electric Co.

TRANSMISSION LINES

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✓ **It matters not that you try and fail,**
And try and fail again,
But it matters much if you try and fail
And fail to try again.
—Stanley B. Smullen

TRANSMISSION LINES

Picked up by the antenna, the television signals must be transferred to the receiver input. The quality of reception depends upon the efficiency with which this energy is transferred, as well as upon the design of the antenna and the receiver. A very important link in the system is the transmission line which carries the energy from the antenna to the receiver.

In general, a **transmission line** consists of a set of conductors employed to carry current of electric power circuits over long distances, or to transfer signal energy from one location to another.

In the case of d-c or low frequency a-c, it may be fairly easy to visualize a flow of electrons in one wire from the source to the load, and a return flow in another wire from the load to the source. Thus, any pair of parallel wires forms a simple transmission line and, together with the source and load, serves to confine the current to a definite path.

However, at higher frequencies, the skin effect forces the current to travel closer to the outer surface of a conductor and causes an increase in the effective resistance. Also, the inductance and capacitance of the conductors, as well as the leakage resistance between them, become of considerable importance. Thus, the various characteristics of any given transmission line must fall within limits which depends upon the frequency range of the signal energy to be transmitted efficiently.

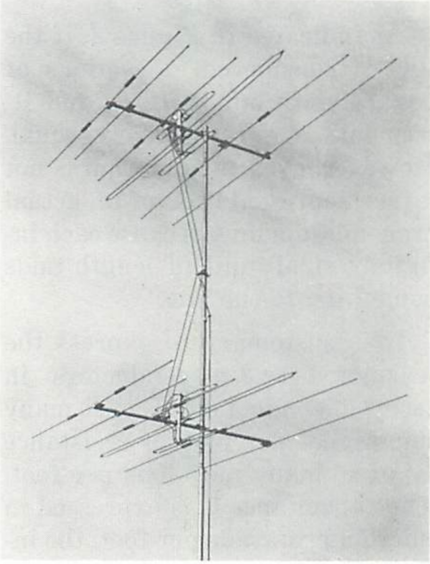
BASIC TYPES OF LINES

Two basic types of transmission lines commonly employed for television are illustrated in Figure 1. In Figure 1A the two-wire parallel conductor contains two conductors which are held at a constant separation and insulated from each other by some material such as polyethylene. Other terms applied to this type of line are TWIN-LEAD and OPEN WIRE LINE. Variations of this construction consist of conductors separated by insulating spacers at intervals; two conductors imbedded in the wall of polyethylene tubing so that the air core of the tubing serves as the dielectric between them; and two polyethylene jacketed conductors which in turn are enclosed in a copper braid shield and a moisture-proof thermoplastic cover. The shield reduces radiation of energy and also pick-up of unwanted energy by the line.

A transmission line using the basic construction shown in Figure 1B is called a COAXIAL CABLE, or CONCENTRIC LINE. In this line, a central wire forms one conductor which is surrounded by a concentric metallic covering that may be flexible or rigid and which forms the second conductor. The central conductor is held at the center of the outer conductor by means of a dielectric material. In some cases, the dielectric consists of a continuous tube of polyethylene, and in others, beads of polystyrene or pyrex are spaced at equal intervals along the inner conductor. The outer conductor confines the transmitted signal energy to the interior of the line, and also serves as a shield to prevent pickup of external energy. When flexible, usually this outer conductor consists of copper braid, and as indicated in Figure 1B, the coaxial cable is protected by a weatherproofing cover of rubber or plastic composition.

LINE CONSTANTS

As explained in an earlier lesson, depending on their construction and the materials of which they are made, all circuits have definite resistance, capacitance, and inductance. While for d-c and low frequency a-c, the resistance is the major factor, at higher frequencies the capacitance and inductance become increasingly important. In addition to resistance, capacitance, and inductance, a transmission line has a property known as SHUNT CONDUCTANCE which is a measure of the leakage current through the dielectric. This current exists because no dielectric is a perfect insulator.



In this stacked array for VHF television reception, the interconnecting harness consists of two-wire transmission lines, while a 300-ohm twin lead ribbon serves as the down-lead to the receiver.

Courtesy Channel Master Corp.

Known as "constants," these properties are distributed evenly along the length of any uniform transmission line, and for convenience, may be indicated schematically as a series of "lumped" components as shown in Figure 2. Here, the series L and R elements represent the resistance and inductance of the two conductors, the capacitors C represent the distributed capacitance, while the shunt conductance is indicated by the resistors R′ to show the paths of the leakage current. Thus, the leakage between conductors may be expressed in the most convenient terms of either conductance G or resistance R′, where G=1/R′.

As indicated in Figure 2, if the line is considered as sections of equal length, all R, L, C, and R′ elements are respectively equal. However, even the diagram is not a true representation of an actual transmission line, because each infinitely small unit of length adds something to the line.

It is customary to express the leakage between conductors in terms of conductance G of so many micromhos per foot, or resistance R′ of so many megohms per foot. The capacitance C is expressed in micromicrofarads per foot, the inductance L in microhenrys per foot, and the resistance R in ohms per foot.

In transmission lines of the types employed for television receiving installations, R and G are small enough (R′ is large enough) to be neglected, leaving L and C as the chief factors to be considered in addition to the load. In most cases, L and C are just as important as the load itself; sometimes they are even more important.

CHARACTERISTIC IMPEDANCE

Each line section of Figure 2 has a definite impedance depending upon R, L, C, and R′, and when connected to a source of alternating voltage will permit some specific current. To increase the length of the line, additional sections must be included, and due to the shunting effect, each added section will reduce the total impedance. However, each added section has less and less effect on the total impedance until finally their effect is negligible. Under these conditions, the line is considered as being infinite in length and the final impedance thus obtained is called the **characteristic impedance,** or **surge impedance (Z_o).**

The magnitude of the characteristic impedance depends upon the size and kind of wire, the inductance and capacitance per unit length, the nature of the medium separating the two wires, and the distance between them. Changes in any of these factors will change the characteristic impedance. Although it is impossible to construct a transmission line of infinite length, it is convenient to rate transmission lines in terms of the impedance Z_o which they would have if infinitely long. By making measurements on a given line of specific length, data can be obtained which permits calculation to a very close approximation of the infinite line impedance.

In each section of the line of Figure 2, two L and two R elements make up the series impedance Z_1, while the C and R′ elements constitute the shunt impedance Z_2. That is, for any one section, the total series resistance $R_T=2R$, and the total series inductance $L_T=2L$. The total series impedance is equal to the vector sum of the resistance and reactance, therefore,

$$Z_1=\sqrt{R_T^2+X_{L_T}^2}.$$

The shunt impedance consists of R′ and C in parallel, equal to their product divided by their sum. Since vector addition is necessary:

$$Z_2=\frac{R'\times X_c}{\sqrt{(R')^2+X_c^2}}.$$

In terms of the series and shunt impedances, the characteristic impedance of the line can be expressed as:

$$Z_o=\sqrt{Z_1\times Z_2},$$

in which:

Z_o=characteristic impedance in ohms,

Z_1=series impedance in ohms per unit length,

Z_2=shunt impedance in ohms per unit length.

As the quantities R and G are negligible for most practical lines, Z_1 almost equals $2\pi fL_T$, and R′ is so much greater than X_C that Z_2 is almost equal to $\frac{1}{2\pi fC}$, at any given frequency f. Thus, substituting these values for Z_1 and Z_2 in the previous equation:

$$Z_o=\sqrt{(2\pi fL)\times\frac{1}{(2\ fC)}}$$

$$=\sqrt{\frac{2\pi fL}{2\pi fC}}$$

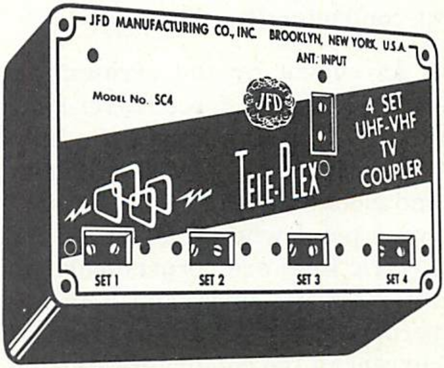
$$=\sqrt{\frac{L}{C}},$$

where:

L=total inductance in henrys per unit length,

C=shunt capacitance in farads per unit length.

This expression assumes that the dielectric separating the conductors is air. In the solid dielectric lines, the impedance Z_o is reduced by the factor $\sqrt{1/K}$, where K is the dielectric constant of the



A coupling network for connecting as many as four receivers to a single lead-in.
Courtesy JFD Mfg. Co., Inc.

insulating material, because it has the effect of increasing the capacitance C per unit length of the line. Thus, for these types of transmission lines:

$$Z_o = \sqrt{\frac{L}{CK}}$$

WAVELENGTH AND VELOCITY

In Figure 3, the small shaded circles A and B represent the conductors of a parallel wire line shown in cross section. At a given instant, a point along conductor A is positive and the corresponding point on B is negative. At this instant, the electric and magnetic fields about these points are as indicated by the solid and dashed lines, respectively. Here, the instantaneous direction of current is assumed to be into the page at conductor A and out of the page at conductor B.

As shown by the arrows, the electric lines of force travel from A to B, while the magnetic lines move counterclockwise around A and clockwise around B. Thus, at every point where they cross, the electric lines are perpendicular to the magnetic lines, and both are perpendicular to the direction of current in the conductors. During succeeding instants, these fields travel along the line, and since they are produced by the moving charges or currents in the wires, they follow the current path, whether curved or straight.

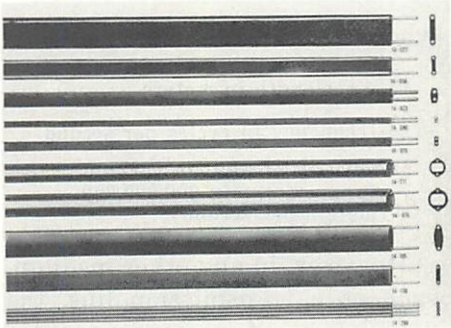
At various points along any one conductor of a transmission line, the current is in different directions as indicated by the arrows drawn in the conductors (A) and (B) of Figure 4A. Also, at the corresponding points (1), (3), and (5), the currents are in opposite directions in the two conductors. The vertical lines represent the electric field between the conductors, and as the arrows on these lines indicate, at points (1) and (5) the conditions are like those illustrated in Figure 3. At point (3), the conditions may be illustrated by reversing the direction of the arrows on all the lines in Figure 3.

Figure 4A indicates conditions at a single instant of time when the currents are zero at points (2) and (4). However, the currents are changing constantly in magnitude, and a certain interval later, will be zero at points (1), (3), and (5). At this later moment, the conditions at points (2) and (4) will be like those illustrated at points (1) and (3) respectively. At a third time, the currents will be zero at points (2) and (4) again, and the fields will have maximum strength at points (1), (3), and (5), but their respective directions will be opposite to those shown.

Thus, due to the changing magnitudes and directions of the currents at various points along the conductors, the regions of maximum and minimum field strength travel along the transmission line in the direction of energy transmission. At the end of a given period of time, conditions again will be as shown in the Figure 4A and the entire series of events occurring during the interval is called a cycle. Thus, the number of cycles which occur each second depends upon the velocity at which the energy travels down the line, and upon the distance between any points, such as (1) and (5), at which like conditions exist.

In Figure 4B, the sine curve indicates the amplitude and direction of the conductor currents and the electric fields at successive points along the line of Figure 4A. However, this curve indicates the conditions at one particular instant only, and it must be moved from the left to right along its horizontal axis to represent the changes which occur with time as the transmitted energy travels along the line. The conductor current and field intensity variations occur in periodic manner, thus it is customary to consider the energy as being transmitted in waves along the line. The wave length is the distance between any point and the next at which the instantaneous conditions are identical, such as between successive peaks of maximum field intensity in the same direction as indicated at points (1) and (5) in Figure 4A.

Indicated by the arrows in the conductors of Figure 4A at the instant shown, the currents have maximum magnitudes at points (1), (3), and (5). Also, as indicated by the concentration of the electric field lines, the difference of potential or voltage between the conductors is greatest at these same points. Thus, in the case illustrated, the voltage and current waves are in phase.



A number of types of flat and tubular twin-lead transmission line. Notice the lower one is a double line.

Courtesy American Phenolic Corp.

For most transmission line applications, this in-phase condition is desirable. The frequency of the waves designates the number of complete waves which pass a given point each second. Therefore, in the case of higher frequencies, more waves pass any given point each second than those of lower frequency. The wave velocity is the same for all frequencies in a given medium such as a transmission line, but the higher frequencies have shorter wavelengths. Thus, with relatively short wavelengths, a larger number of high frequency waves can pass a given point each second, even though their velocity is the same as the lower frequency waves.

When electromagnetic energy waves are traveling in free space, their wavelength is given by the expression:

$$\lambda=\frac{c}{f}$$

where:

λ = wavelength in meters

f = frequency in cycles per second

c = velocity of light in vacuum (approximately 300,000,000 meters per second).

However, in any other medium, such as a transmission line, the velocity v of electromagnetic waves is less than the free space velocity c. Thus for waves of the same frequency f, the wavelength λ' in a transmission line for example is given by,

$$\lambda'=\frac{v}{f}$$

These equations can be rearranged to read $f=c/\lambda$ and $f=v/\lambda'$.

Since quantities which are equal to the same quantity are equal to each other:

$$\frac{v}{\lambda'}=\frac{c}{\lambda},$$

and this may be inverted to give:

$$\frac{\lambda'}{v}=\frac{\lambda}{c}.$$

Finally, multiplying both sides by v gives:

$$\lambda'=\left(\frac{v}{c}\right)\lambda$$

Since v is some positive number between zero and c, the factor v/c is always some fraction between 0 and 1. Therefore, this last equation shows that the wave length in the transmission line is always less than in free space.

LINE TERMINATION

Figure 5 shows a transmission line, L_1, connected between a source of energy and a load. The end of the line connected to the generator or other source is called the SENDING END, while the other end is designated the RECEIVING END. The load may be a resistance, reactance, or impedance, and is said to "terminate" the transmission line. However, there are applications in which the line is not terminated in a load of this type. For example, in place of the load, a short circuit may be connected across the receiving end of the line. Terminated thus in a short, the line is called a **shorted**

line. A line may be terminated in an open circuit also, in which case it is called an **open line.** The properties and uses of shorted and open lines are explained in later sections of this lesson. For the present, we want to mention only that the voltage, current, and impedance conditions in a transmission line depend upon the nature of its termination.

A generator connected to the sending end of a transmission line of infinite length is depicted by the drawing of Figure 6. In this arrangement, the characteristic impedance of the line forms the load into which the generator operates. The vertical dashed line divides the transmission line into two sections, a finite length L_1, and an infinite length L_2. If L_2 is disconnected from L_1, the L_2 section is still of infinite length, and has the same characteristic impedance as before. If in place of L_2, the receiving end of L_1 is terminated in a load equal to the characteristic impedance of the line, then the circuit is like that of Figure 5. So far as the generator is concerned, circuit conditions are the same as though the generator was delivering its output to the infinite line of Figure 6.

NONRESONANT LINE

When a transmission line is terminated in a load equal to the characteristic impedance of the line, the current and voltage waves remain in phase for the entire length of the line. In this respect the line acts as though it had infinite length.

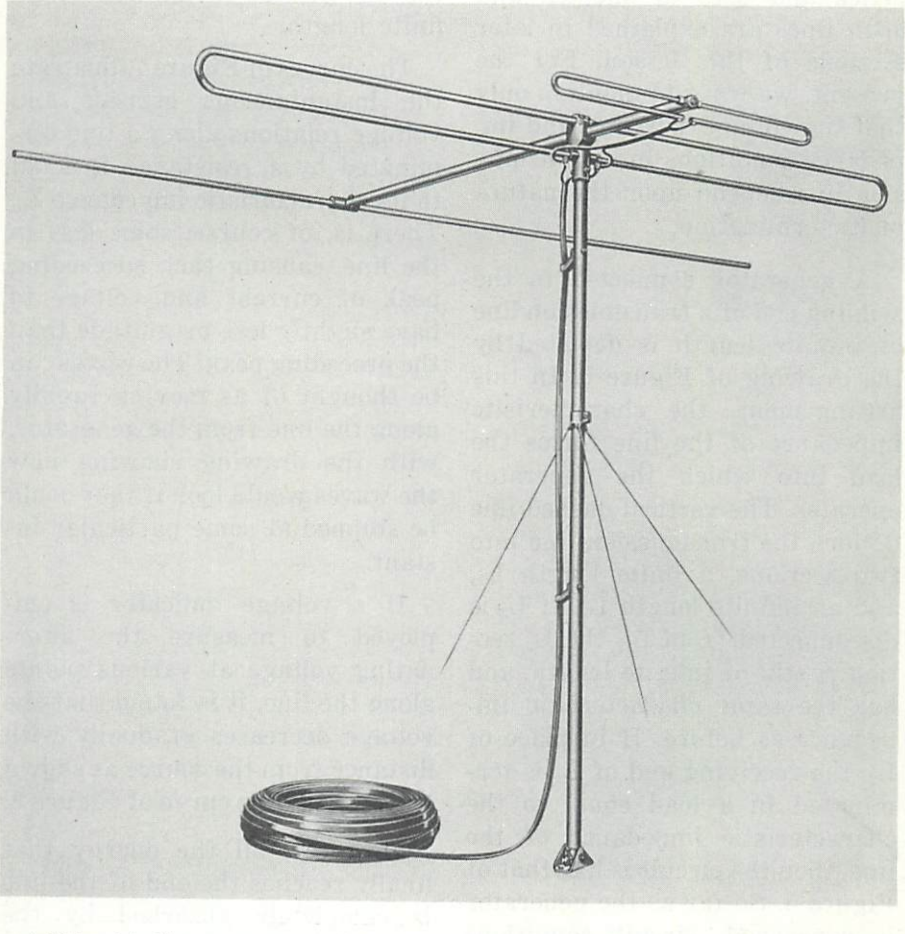
The curves of Figure 7 illustrate the instantaneous current and voltage relations along a line terminated by a resistance R equal to its characteristic impedance Z_0. There is, of course, some loss in the line, causing each succeeding peak of current and voltage to have slightly less magnitude than the preceding peak. The waves can be thought of as moving rapidly along the line from the generator, with the drawing showing how the waves would look if they could be stopped at some particular instant.

If a voltage indicator is employed to measure the alternating voltage at various points along the line, it is found that the voltage decreases gradually with distance from the source as shown by the solid line curve of Figure 8.

However, all the energy that finally reaches the end of the line is completely absorbed by the load. A transmission line operated in this manner, that is, terminated with a resistor R equal to Z_0, is known as a NONRESONANT LINE.

RESONANT LINE

A line terminated by a load which is not equal to its characteristic impedance is called a RESONANT LINE. When the waves reach the receiving end of a resonant line, the energy is not absorbed completely by the load. Instead, some is reflected back toward the source. At any point along the line, the voltage and current magnitudes are equal to the algebraic sum of the outgoing and reflected waves at that point. Because both waves move with the same speed but in opposite directions, at certain points along the line, the voltage E and the current I are minimum at all times. Midway between these points, E and I rise alternately to



A hi-low television antenna. To effect greatest transfer of energy from antenna to receiver, the impedances of the antenna, transmission line, and receiver input must be matched.

Courtesy American Phenolic Corp.

maximum in one direction and then in the other. As they do not move along the line, these variations of E and I are known as **standing waves.**

Figure 9 illustrates two conditions which result in standing waves. The curves of Figure 9B show the location of the standing waves of voltage when the line of Figure 9A is terminated in a resistance R which is greater than Z_0. Since these curves illustrate the standing waves only, for simplicity both positive and negative alternations are drawn upward on the graph. The right hand end of the graph indicates the voltage at the load terminals.

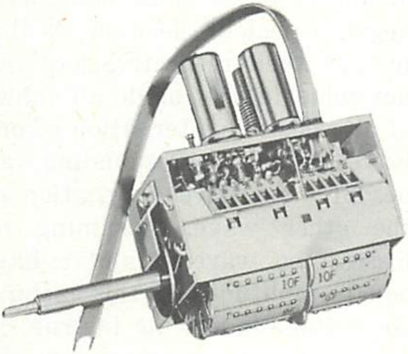
As shown in Figure 9B, when the load resistance R is greater than the characteristic line impedance Z_0, the voltage at the load terminals is greater than the input voltage. On the other hand, when the load resistance R is less than the line impedance Z_0, the voltage across the load is less than the input voltage, as shown in Figure 9C.

HOW STANDING WAVES ARE PRODUCED

The production of a standing wave is demonstrated by the curves of Figure 10. Here, the solid line curves represent the incident wave, i, which originates at O and travels toward T, the termination of the transmission line. The reflected wave, r, moves along the line in the direction from T to O. Assume, for example, that waves i and r are voltage waves, and that a voltage indicator is employed at various points along the line to measure the voltage between the two conductors forming the line. At any given point, the magnitude of neither wave i nor wave r is indicated by the instrument. Instead, the algebraic sum of the voltage waves is indicated.

Figure 10A shows the two traveling waves at an instant when, with i moving to the right, and r moving to the left, a positive peak of one is at the same point as a negative peak of the other. At this instant, their respective zero values coincide also, as do all values of any positive alternation of one wave and the corresponding values of a negative alternation of the other wave. Assuming no losses, the waves i and r have equal amplitude. At this instant, the voltage indicating instrument reads zero, at any point along the line. For example, at point 1, a quarter wavelength from T, the positive peak of wave r cancels the effect on the meter of the negative peak of wave i. At point 2, both waves are at zero. At point 3, peaks again have opposite polarity. At point 4, again both waves are at zero, and so on.

In Figure 10B, both waves have traveled a distance of 45°, in the respective directions indicated. Since their directions are opposite, they have a total displacement of 90° with respect to their phase relation of Figure 10A. At this instant, the voltage indicator reads zero at points 1 and 3 where the respective waves have equal but opposite values. At point 2, both waves are positive, and the meter shows a positive value equal to their sum. At point 4, both waves are negative, and a negative value equal to their sum is obtained. If readings are taken at many points, the indicated values along the line vary as shown by curve S.



The 300 ohm twin lead transmission line is terminated in its characteristic impedance in the television tuner.

Courtesy Standard Coil Products Co.

After traveling in their respective directions for another 45° each, waves i and r coincide as shown in Figure 10C. At this instant, their positive and negative peaks add, respectively, to produce maximum meter readings as indicated by the peaks of curve S. All curves cross the zero axis at points 1 and 3. Figure 10D shows conditions 45° later, where curve S has decreased to the same amplitude as in Figure 10B.

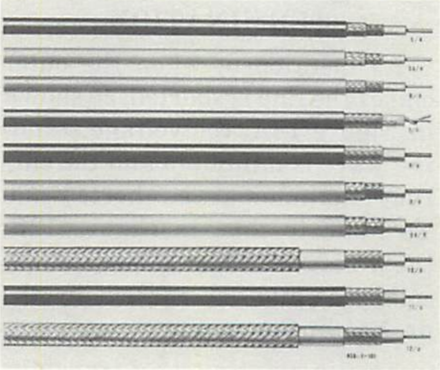
As shown in Figure 10E, after each wave has moved a total of 180°, they have the same phase relationship, relative to each other, as in Figure 10A. Therefore, indicated by the letter S at the axis, the sum of the waves has reduced to zero at all points. As the travelling waves continue along the line in their respective directions, their values add algebraically to produce total values from point to point as shown by the curve S in Figure 10F. Notice here, at point 4, curve S has a positive peak in place of the negative peak at this point in Figure 10B. In Figure 10G, the traveling waves coincide, and wave S has maximum amplitude. Finally, in Figure 10H, each travelling wave has moved a total of 360° along the line, their phase is the same as in Figures 10A and 10E, and wave S has fallen to zero. As waves i and r continue from this point, the entire cycle of events is repeated.

Compare the curves labeled S in the various stages of Figure 10. The S curve crosses the zero axis at points 1 and 3. In this example, these points are ¼ and ¾ of a wavelength, respectively, from the termination of the line at T. The peaks of the curve occur at points 2 and 4, and all other multiples of a half-wavelength from T. Indicated by curve S in Figure 10C, the sum voltage rises from zero to a positive peak at point 2 and a negative peak at point 4, falls to zero in Figure 10E, then reaches a negative peak at point 2 and rises to a positive peak at point 4 (Figure 10G), and again falls to zero (Figure 10H).

Points 1, 2, 3, and 4, and successive points, are at the same respective positions along the line. Thus, corresponding to these points, the alternate peaks and zero values of the sum voltage remain at the same respective positions on the line also. That is, with the particular termination assumed for this example, as the voltage indicator is moved along the transmission line, it gives minimum or zero readings at all points which are at distances equal to multiples of quarter-wavelengths from T. The indicator gives maximum readings at all points located at multiples of one-half wavelength from T. At other points, the voltage has intermediate values as indicated by curve S in Figure 10C or 10F.

Because the voltage wave S does not travel along the line, but instead remains stationary, it is called a standing wave. As explained, although the standing wave does not move along the line, it does vary continually in amplitude.

Another representation of this variation is given in Figure 11. Here, the numbered curves show a series of instantaneous values of the standing wave. The first curve coincides with the axis to represent the zero value of the standing wave. As this wave increases in amplitude, it is represented successively by curves 2, 3, 4, and so on up to the maximum indicated by curve 8. The wave then decreases through the values shown by curves 7, 6, 5, and so to zero. For the second half of its cycle, the standing wave rises to maximum in the opposite direction, as represented by curve 9, after which it again falls to zero to complete the cycle.



Coaxial cable transmission lines of various construction and sizes.
Courtesy American Phenolic Corp.

In addition to a standing wave of voltage, there is also a standing wave of current produced along a resonant line. The phase relation between the voltage and current standing waves depends upon the termination of the line. For example, with a line terminated in an open circuit, the standing wave of voltage is a maximum at the open end of the line, as in Figure 10. In this case, the standing wave of current is minimum at the termination point, as in Figure 11, thus the two standing waves are 90° out of phase. As another example, the voltage wave has the position of that of Figure 11, and the current wave that of Figure 10, when the line terminates in a short. Again the two standing waves are 90° out of phase. Described later in this lesson, other terminations produce other phase relations.

EFFECT OF LINE TERMINATION

As mentioned, when the outer end of the line is shorted, as shown in Figure 12A, the voltage standing wave is minimum and the current maximum at the shorted end. To indicate this, in Figure 12B, the voltage is represented by the solid line and the current by the dashed line curves.

At any point along a transmission line, the impedance Z is equal to E/I. In the case of a nonresonant line, the ratio of voltage to current is the same at all points, although both voltage and current decrease with distance from the source. Therefore, E/I is a constant equal to the characteristic impedance Z_0 at all points along the line.

In the case of a resonant line, the ratio E/I varies from point to point, and therefore, line impedance Z_0 also varies. For example, with the shorted line of Figure 12A, the voltage is minimum at the short, and the current maximum. Thus, calculated from the ratio E/I, Z is minimum at the shorted end. However, as shown in Figure 12B, at a point located one-quarter wavelength back from the shorted end, E is maximum and I is minimum. Therefore, at this point on the line, $E/I=Z$ is maximum.

The transmission line of Figure 13A is open at the end, with the resulting standing wave conditions shown by the solid line voltage curve and dashed line current curve in Figure 13B. In this case, the current is minimum at the open end, and the voltage maximum. Thus, the impedance Z is maximum at the end of an open line. At a point one-quarter wavelength back from the open end of the line, E is minimum and I maximum, thus $E/I=Z$ is minimum at this point.

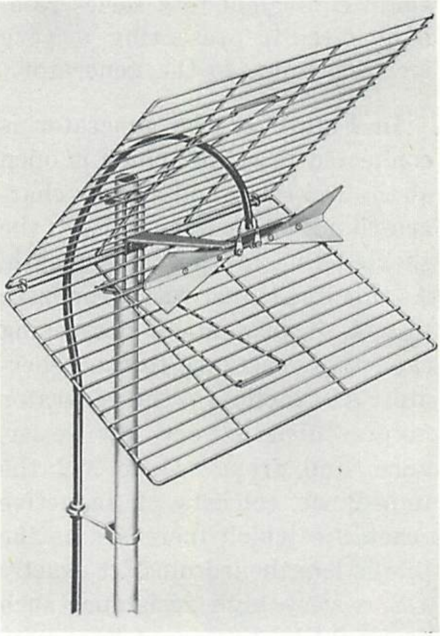
In Figure 14A, the transmission line is terminated by a capacitive load, and as shown in Figure 14B, the voltage at the load is between the maximum and minimum values of the standing wave. In fact, the voltage across C varies inversely with its capacitance. As the capacitance is reduced, the voltage at the load increases, and the standing wave "moves" toward the left in Figure 14B, thus approaching the conditions in the open end line of Figure 13B.

A line terminated by an inductive load and the resulting voltage standing wave are illustrated in Figure 15. In this case, the voltage varies directly with the inductance of coil L, and has some value between the maximum and minimum of the standing wave. As L decreases, the voltage at the load end of the line decreases also, and the standing wave shifts toward the left on the graph to approach the shorted line conditions of Figure 12B.

IMPEDANCE VARIATION ALONG TRANSMISSION LINE

In order to see how the transmission line characteristics depend upon its length, consider a generator which produces a signal of frequency f, and a two-wire line which has variable length and is short-circuited at the receiving end, as illustrated in Figure 16. Here, the double arrowed line is the "shorting bar". Also, the wavelength is designated by the Greek letter Lambda (λ).

As the shorted line is increased in length from zero to λ/4, to the generator it acts, or "looks" like an inductive reactance of increasing magnitude. This is illustrated by the symbol for a coil between 0 and λ/4 in the lower left in the figure. At exactly one-quarter wavelength, the line acts like a very high resistance, or a parallel resonant circuit, as indicated above the line at λ/4. Between one-quarter and one-half wavelength, the line acts like a capacitive reactance of decreasing magnitude until, at exactly λ/2, it acts like a series resonant circuit or a low resistance.



Corner reflector antenna employing shielded pair transmission line for UHF reception.
Courtesy American Phenolic Corp.

Between $\lambda/2$ and $3\lambda/4$ it again acts like an inductance and presents an increasing inductive reactance to the generator. At exactly $3\lambda/4$ it again behaves like a parallel resonant circuit, and from $3\lambda/4$ to λ, presents a decreasing capacitive reactance. At λ it is again equivalent to a series resonant circuit, presenting a very low resistance to the generator.

In Figure 17 the generator is connected to a line which is open at the receiving end and its characteristics differ from those of the shorted line of the same length. As this line is increased from zero to $\lambda/4$, it presents a decreasing capactive reactance to the generator. At exactly $\lambda/4$ the generator is presented a very low resistance, and from $\lambda/4$ to $\lambda/2$ the impedance consists of inductive reactance which increases as the line is lengthened until at exactly $\lambda/2$, a very high resistance such as would be presented by a parallel resonant circuit is "seen" by the generator.

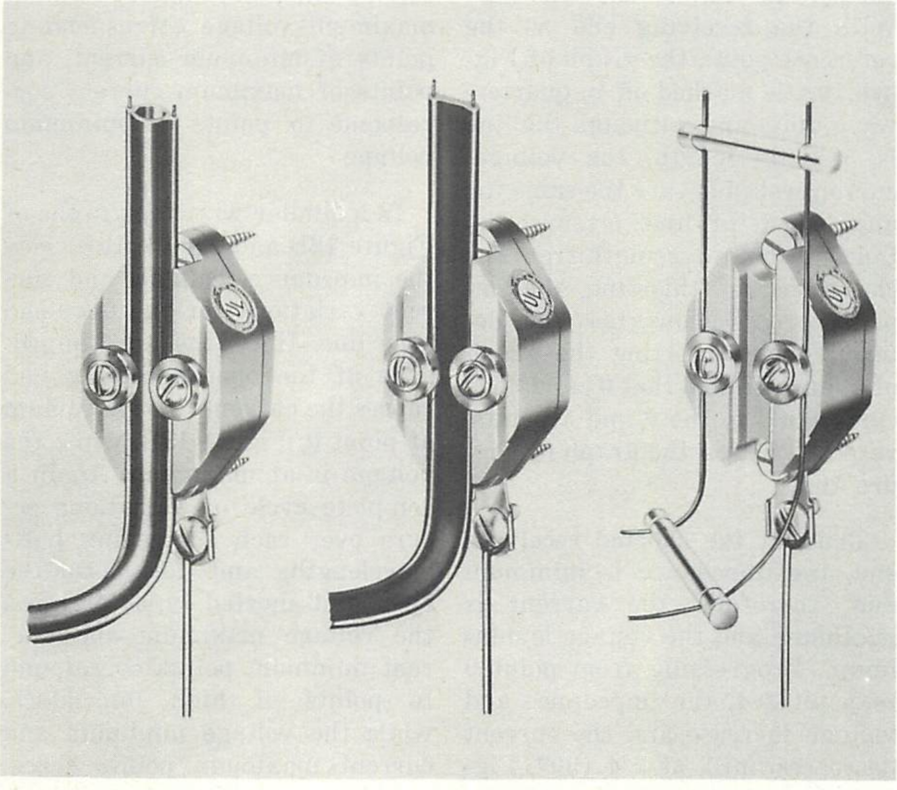
A decreasing capacitive reactance is presented from $\lambda/2$ to $3\lambda/4$, and the low resistance of a series resonant circuit at exactly $3\lambda/4$. From $3\lambda/4$ to λ, the line presents an increasing inductive reactance, and at λ, the very high resistance equivalent to a parallel resonant circuit is presented to the generator.

As in the case of the line shorted at the receiving end, to the generator the open-end line presents an impedance which varies with the length of the line. Notice that, at even multiples of a quarter wavelength, the shorted line acts like a low resistance or a series resonant circuit, while the open line acts like the very high resistance of a parallel-resonant circuit.

In the study of transmission lines, often it is convenient to think of a given line in terms of degrees rather than linear length. With this system, a distance representing one wavelength is considered as 360°, a half wavelength 180° and a quarter wavelength 90°. With the length given in degrees and the corresponding values and nature of the impedance given by the curves, the manner in which the impedance varies with the length of a transmission line is shown in Figure 18. Above the horizontal axis the reactance is inductive and is represented by X_L. Below the axis the reactance is capacitive and is represented by X_C.

The curves of Figure 18A are for a short-circuited line, and starting from 0°, the reactance is inductive and becomes equal to the characteristic impedance of the line at point P, which represents $\lambda/8$, or 45°. As the line length approaches 90° (one-quarter wavelength), the impedance rises rapidly to a very high value. This is shown in Figure 16 also, where at λ/4 the impedance is equivalent to the high resistance presented by a parallel resonant circuit.

Above 90°, the reactance is still high but is now capacitive. It is equal to the characteristic impedance (Z_o) at 135° (3λ/8), and drops to zero at 180° (λ/2). In Figure 16, the impedance is indicated as a Low R at this point, and as mentioned, is equivalent to a series resonant circuit. From earlier explanations it is known that, in a series resonant circuit, the impedance depends upon the resistance of the wire in the circuit. If the wire is large and is a very good conductor, the resistance is negligible. For this reason it is shown as zero at 180° in Figure 18A. Continuing beyond 180,° the line reactance varies the same as for the first 180°, and, at 360°, again drops to zero.



Showing connection of tubular, ribbon, and open-wire type lines to lightning arrestors.

Courtesy American Phenolic Corp.

Interpreted in the same manner, Figure 18B gives corresponding reactances for the open-circuited line of Figure 17. A comparison of Figures 18A and 18B shows the important differences in the impedances of open and shorted lines.

The current and voltage relations in both the shorted or closed-end and the open-end lines are shown in Figure 19. Here, the solid line curves give the voltages along the lines, and the dashed-line curves the currents. With the receiving end as the reference point, the graph of Figure 19A is marked off in quarter-wave units and, although the line is $5\lambda/4$ in length, the voltage-current relations are the same for any length of line. Over a distance of one wavelength from the closed end of this line, the impedance variations may be determined by applying the graph of Figure 18A so that 0° and 360° correspond to the 0 and λ points, respectively, on the graph of Figure 19A.

Thus, at the shorted receiving end, the impedance is minimum and, therefore, the current is maximum and the voltage is minimum. Progressing from point 0 to point $\lambda/4$, the impedance and voltage increase and the current decreases until, at $\lambda/4$ (90°, Figure 18A), the impedance and voltage are maximum and the current is minimum. Beyond $\lambda/4$, the impedance and voltage decrease and the current increases until, at $\lambda/2$ (180°), the current is maximum and the impedance and voltage minimum.

A similar cycle of variations occurs over each succeeding half-wavelength of the line until the generator is reached. Notice that points of maximum voltage, E_m, and points of maximum current, I_m, are spaced at alternate quarter-wave intervals from the receiving end, and that points of maximum voltage correspond to points of minimum current, and points of maximum current correspond to points of minimum voltage.

In a similar way, the graphs of Figure 18B and Figure 19B show the impedance, voltage, and current variations for the open-end type line. Here, the high impedance of the open receiving end causes the current to be minimum at point 0, Figure 19B, while the voltage is at maximum. Again a complete cycle of variations occurs over each succeeding half-wavelength, and for both the open and shorted types of lines, the voltage maximum and current minimum points correspond to points of high impedance, while the voltage minimum and current maximum points correspond to points of low impedance.

Regardless of line length with respect to signal wavelength, standing waves are always produced if the line is not terminated by a resistance equal to its characteristic, or surge impedance. The maximum voltage and current in Figure 19, are called LOOPS, while the minimum values are called NODES.

If, instead of being shorted or open, the transmission line is terminated by pure inductance or pure capacitance, the loops and nodes are shifted along the line, but retain their respective quarter-wave spacing. The first voltage loop and current node is less than a quarter wavelength from the end of the line if the termination is inductive, while the first current loop and voltage node is less than a quarter wavelength from the end if the termination is capacitive. In each case, the displacement is proportional to the terminating inductance or capacitance.

When the terminating load is purely resistive but not equal to Z_0, some power is consumed by the load, and some is reflected to cause standing waves. Again, the distribution of current and voltage loops and nodes is the same as shown in Figures 19A or 19B. However, the node values are no longer zero but have a value proportional to the power delivered to the load.

For example, in Figure 20 the line is terminated by resistance $R=3Z_0$, and there is a voltage loop and current node at the receiving end of the line as indicated by the graph. In Figure 21, the load resistance is equal to one-third of Z_0, and the receiving end of the line has a current loop and a voltage node. In both figures, the maximum and minimum levels are indicated by dashed horizontal lines, and as the resistance of R is made closer and closer to Z_0, these horizontal lines approach each other until, as shown in Figure 22, when $R=Z_0$, they form a single line and no standing waves exist.

On the other hand, the greater the difference between R and Z_0, the greater the spacing between the horizontal dashed lines of Figures 20 and 21. That is, the greater the impedance mismatch between the transmission line and the load, the greater the amplitude of the standing waves. When the load contains inductive or capacitive reactance as well as resistance, the nodes are greater than zero as in Figures 20 and 21, but the waves are shifted along the line as explained for pure reactive terminations.

STANDING WAVE RATIO

Representing the measure of mismatch between the transmission line and its load, the ratio of the voltage or current at the loops to the values at the nodes is known as the STANDING WAVE RATIO, which is abbreviated SWR and stated mathematically by:

$$SWR = \frac{E_{max}}{E_{min}}, \text{ or } \frac{I_{max}}{I_{min}}.$$

The ratio of mismatch also may be expressed in terms of the impedances by:

$$SWR = \frac{Z_o}{R}, \text{ or } \frac{R}{Z_o}.$$

A portable television receiver. The television receiver is the load to which the transmission line should deliver the signal with as little loss as possible.

Courtesy Emerson Radio and Phonograph Corp.

Two forms of this equation are given so that the common practice of stating standing wave ratios in whole numbers always may be employed.

On a transmission line carrying considerable r-f power, such as that connecting a transmitter to the radiating antenna, the voltage loops and nodes are of sufficient magnitude to permit their being measured by moving an r-f indicator along the line, after which the SWR may be computed, using the equations already given. For example, in Figure 20 the line is terminated with a resistance greater than the characteristic impedance so that the voltage and current vary as shown in the graph. Assuming that 3 volts maximum and 1 volt minimum are measured, the standing wave ratio is:

$$SWR = \frac{3}{1} = 3.$$

Terminated with a resistance lower than the characteristic resistance, the line of Figure 21 also has standing waves on it. If measuring the voltages results in readings of 3 volts maximum and 1 volt minimum,

$$SWR = \frac{3}{1} = 3.$$

The load resistance of Figure 22 is the same as the characteristic impedance, and therefore, the meter indicates a constant voltage along the line as shown by the graph. In this case the SWR is 1, the line is said to be "flat", and maximum energy is delivered to the load.

In a receiving transmission line there is not enough r-f energy to make possible the measurement of voltage and current. However, the standing wave ratio may be determined when the load resistance and characteristic impedance are known. In Figure 20, $R=3Z_o$, hence:

$$SWR=\frac{R}{Z_o}=\frac{3}{1}=3,$$

which is the same as previously calculated.

In like manner, in Figure 21, $R=Z_o/3$ and:

$$SWR=\frac{Z_o}{R}=\frac{1}{1/3}=3.$$

The line of Figure 22 is terminated with a load resistance equal to the characteristic impedance, and:

$$SWR=\frac{R}{Z_o}=1.$$

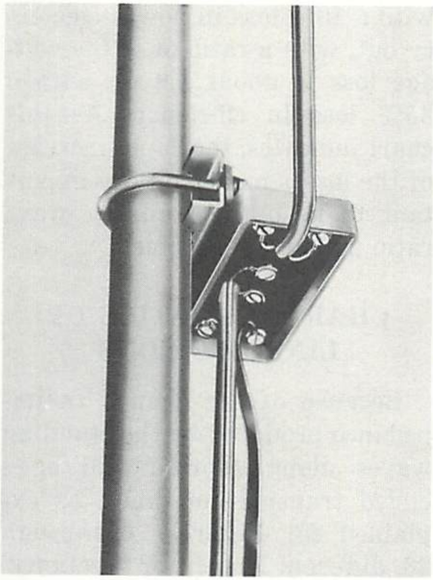
In Figures 20, 21, and 22, the generators may represent the television receiving antenna, the transmission lines the lead-in from antenna to receiver, and R the receiver input impedance. If R is much greater or less than the line characteristic impedance Z_o, the transmission line and the receiver input are not properly matched; therefore the standing wave ratio will be high and reception unsatisfactory.

The relationship between voltage losses in db and power efficiency in percent to the standing wave ratio are shown by the curve of Figure 23. For example, with a ratio of 2, the voltage loss is .5 db with a 10% loss in power efficiency but, with a ratio of 4, the voltage loss is about 1.8 db with a 35% loss in efficiency. As this chart indicates, the rapid increase of the losses makes it very important to keep the standing wave ratio as low as possible.

CHARACTERISTICS OF LINE SECTIONS

Because of the change in impedance produced by the standing waves along shorted and open ended transmission lines, as explained for Figures 16 through 23, different lengths or "sections" of such lines are employed as various types of circuit elements in electron equipment. Such sections vary in length, and should not be confused with the extremely short "theoretical sections" mentioned above in connection with Figure 2. As an example, it was mentioned that at a point one-quarter wave from the shorted end of a line, the impedance Z reaches a maximum. In fact, if the line losses are low, this maximum Z is extremely high.

Since this condition is like that at the terminals of a parallel resonant circuit, a shorted line section of one-quarter wavelength is the equivalent of a parallel resonant circuit. Like the resonant circuit, the shorted quarter-wave section has this very high impedance at a single frequency only, this frequency being that at which the line length is equal to a quarter-wavelength ($\frac{1}{4}\lambda$) of the signal applied to the input terminals of the line.



This coupling filter passes to the down-lead the VHF signals from the flat twin lead, which is connected to the VHF antenna, and the UHF signals from the tubular twin lead which connects to the UHF antenna. The down-lead connects to the input terminals of the receiver.

Courtesy JFD Mfg. Co., Inc.

Such a shorted section is illustrated in Figure 24A. Here x and y are the input terminals, and D is the length of the line section. Thus, as indicated by the arrow, when "looking into" the line at the input terminals, the impedance which is "seen" depends upon the length D relative to one-quarter wavelength of the signal applied at x and y. As mentioned, the impedance seen at x and y is very high when D is equal to $\frac{1}{4}\lambda$.

Referring again to Figure 12B, when the length D of the line section is less than $\frac{1}{4}\lambda$, the impedance Z seen at terminals x and y of Figure 24A is some value E/I between maximum and minimum. Also, in this region, the voltage standing wave curve is like that at the extreme right end of the line in Figure 15. Therefore, at its input terminals, a shorted section which is less than $\frac{1}{4}\lambda$ long "looks" like an inductance.

When the shorted section is greater than $\frac{1}{4}\lambda$ in length, again the impedance at its input terminals is between maximum and minimum, and the voltage standing wave is like that at the end of the line of Figure 14. Thus, at its input terminals a shorted section with length D greater than $\frac{1}{4}\lambda$ looks like a capacitance.

When the length D, Figure 24A, is equal to one-half wavelength, Z is minimum, and the section acts like a series resonant circuit. Similar equivalent conditions exist in the case of the open ended line section of Figure 24B. Here, looking in at terminals x and y the impedance is very low, nearly zero, when D is equal to ¼λ, therefore, the line section is equivalent to a series resonant or a short circuit. On the other hand, when D is equal to ½ λ, the impedance is very high, and the section is equivalent to a parallel resonant or an open circuit. An open section looks like a capacitance at its input terminals if its length D is less than ¼λ, but if D is between ¼λ and ½λ, the input terminals present an impedance which looks like an inductance.

Figure 24C shows a line section which is terminated by a simple or complex circuit element of impedance Z which provides conditions other than an open or short at that end of the line. In this case, the impedance seen at x and y depends not only on the length of the section, but also upon the nature of Z.

For various section lengths and terminations, Table 1 lists the type and relative magnitude of the impedance which is presented to the signal applied to the input terminals x and y of the line sections of Figure 24. The listed terminations consist of opens, shorts, and resistances greater than, equal to, or less than the characteristic impedance Z_0 of the line.

As the table shows, a quarter-wave section "inverts" the load impedance such that the opposite magnitude is presented by the input terminals. A half wave section presents the same impedance at the input as is provided by the termination at the load end of the line. When the termination is a resistance R greater or less than Z_0, the other sections present input impedance with a reactive component. In all cases, the input impedance is Z_0 when R is equal to Z_0. If a line having length equal to some multiple of a half wavelength is added to any of the above transmission line sections, the impedance characteristics at the input terminals are the same as the input of the original section.

APPLICATIONS OF LINE SECTIONS

Because of their electrical equivalence to various circuit elements, transmission line sections are employed wherever the ordinary lumped type elements are impractical, such as in VHF, UHF, and SHF equipment. Technically, these sections could be employed in lower frequency circuits also, but are impractical because of their excessive lengths. Of course, there is a border line frequency band in which either the line section or lumped type circuit elements may be used, and the choice must be determined by other design factors.

Impedance Matching

A useful property, known as impedance matching, is provided by the characteristics of a quarter wave line if the input impedance Z_{in}, the output impedance Z_{out} and the characteristic impedance Z_o have the relationship:

$$Z_o^2 = Z_{in} \times Z_{out}$$

This relation may be expressed as:

$$Z_o = \sqrt{Z_1 \times Z_2}$$

TABLE 1

Length of Line	With Line Load End Terminated in	At Input the Line looks like a
Less than ¼ λ	Open	Capacitance
	R greater than Z_o	Capacitance and resistance in series
	R equal to Z_o	Resistance equal to Z_o
	R less than Z_o	Resistance and inductance in series
	Short	Inductance
¼ λ	Open	Short, or series resonant circuit
	R greater than Z_o	Resistance less than Z_o
	R equal to Z_o	Resistance equal to Z_o
	R less than Z_o	Resistance greater than Z_o
	Short	Open, or parallel resonant circuit
Between ¼ λ and ½ λ	Open	Inductance
	R greater than Z_o	Inductance and resistance in series
	R equal to Z_o	Resistance equal to Z_o
	R less than Z_o	Capacitance and resistance in series
	Short	Capacitance
½ λ	Open	Open
	R greater than Z_o	Resistance equal to R
	R equal to Z_o	Resistance equal to Z_o
	R less than Z_o	Resistance equal to R
	Short	Short

when,

Z_o = characteristic impedance of the line in ohms

Z_1 = input impedance in ohms

Z_2 = output impedance in ohms

Rearranging the equation to the form:

$$Z_{in} = \frac{Z_o^2}{Z_{out}},$$

the inverse relationship between the input and output impedance of a ¼ wavelength line is shown more clearly. As Z_o is generally a resistance, the equation indicates that the product of $Z_{in} \times Z_{out}$ also is a resistance. Although Z_{in} may contain an inductive reactance and Z_{out} a capacitive reactance, their vector product result is a resistance.

Referring to Figure 18B, it is seen that a line of ¼ wavelength is equivalent to 90° of the electric cycle. In changing from minimum to maximum, or vice versa, the impedance is said to be converted. It is this conversion of impedance which makes it possible to employ the line for impedance matching.

For example, assume it is desired to match a 500 ohm line to a 72 ohm antenna. Substituting in the above equation, with $Z_1 = 500$ ohms and $Z_2 = 72$ ohms:

$$Z_o = \sqrt{Z_1 \times Z_2} = \sqrt{500 \times 72}$$
$$= 190 \text{ ohms (approx.)}$$

Therefore, a line with a characteristic impedance of 190 ohms will effect an impedance match between the 500 ohm input line and the 72 ohm antenna.

In addition, line sections are employed as tank circuits in oscillator, amplifier, and converter stages. They are used as series or parallel resonant circuits for wave trap purposes. Other uses include filters, phase converters, switching circuits, insulators, connecting a balanced circuit to an unbalanced circuit, and making standing wave measurements.

DELAY LINES

For any type of transmission line, it takes a short but definite time for a given applied signal to travel from one end of the line to the other. This fact is made use of in electron applications in which it is necessary to delay the signal by some time interval, and a transmission network used for this purpose is known as a **delay line.** Delay lines are employed as part of pulse generating circuits, for delaying pulses, and as a means of obtaining the desired pulse waveform. In these applications, usually the delay time (t_d) is on the order of 10 microseconds or less.

As explained previously, unless a transmission line is terminated by resistance equal to its characteristic impedance Z_o, energy will be reflected at the load or receiving end and travel back along the line to the sending end. Also, unless the signal source impedance is equal to Z_o, the reflected energy will be reflected at the sending end and travel toward the receiving end again. For delay lines, reflection from the receiving or load end of the line is desirable. To prevent distortion of pulse type signals, the reflecting end either must be open, shorted, or terminated in pure resistance.

The magnitude of the reflected energy relative to that applied to the input end of the line may be expressed in terms of the **coefficient of reflection** (K), which is defined as the ratio of the difference to the sum of the characteristic impedance Z_o of the line and the terminating load resistance R_L. That is:

$$K=\frac{R_L-Z_o}{R_L+Z_o}.$$

TYPE OF LINE	SURGE IMPEDANCE		ATTENUATION IN DB PER 100 FT. AT		EFFICIENCY IN %		MAXIMUM RECOMMENDED LENGTH IN FEET		BALANCED OR UNBAL.	SHIELDED OR UNSH.
	FROM	TO	50 MC	500 MC	VHF	UHF	VHF	UHF		
(A) TWISTED PAIR	40	150	6.50	—	22	—	50	—	BAL	UNSH.
(B) TWIN LEAD	75	300	.85	5.7	82	27	150	50	BAL.	UNSH.
(C) TUBULAR TWIN LEAD	75	300	.69	3.4	85	46	200	100	BAL.	UNSH.
(D) COAXIAL	48	150	.40	5.0	92	32	400	50	UNBAL.	SH.
(E) SHIELDED PAIR	90	150	3.00	—	50	—	100	—	BAL.	SH.

Table compares characteristics of the various types of transmission lines employed for television reception.

When the line is shorted at the load end, $R_L=0$, and K is equal to -1. All the energy is reflected, but the reflected signal is inverted, or shifted in phase by 180°. For a sine wave signal, this condition is illustrated in Figure 25A where the solid sine curve represents the waves traveling from the input end of the line toward the load R_L and the dashed curve represents the reflected waves. The same conditions are shown in Figure 25B where the signal consists of a series of rectangular pulses.

When the line is terminated in resistance less than Z_o, the same phase relations exist as shown in Figures 25A and 25B, but the reflected waves or pulses have less amplitude. When $R_L=Z_o$, all the energy is transferred to the load and there is no reflection since $K=0$.

When the load consists of resistance greater than Z_o, then some energy is absorbed by R_L

and some reflected, but the reflected waves or pulses have the same polarity as before reflection. That is, reflection at the load occurs without inversion of the signal. Finally, all the energy is reflected without inversion when the line is open at the load end. Then R_L is equal to infinity, and K is equal to +1. For pulse signals, this condition is illustrated in Figure 25C where the reflected (dashed line) pulses are shown returning back along the transmission line with the same polarity as the incoming pulses.

For many applications, an impractical length of ordinary transmission line would be required to obtain the needed delay time t_d. In such cases, it is common practice to substitute an artificial line consisting of a series of LC sections as shown in Figure 26. Here, each section corresponds to the sections of a real transmission line, having series inductance and shunt capacitance as explained for Figure 2. Thus, whereas Figure 2 shows how an actual transmission line is equivalent to a series of similar RCL networks, Figures 2 and 26 may be compared to show that an artificial line, containing lumped L and C components, is basically like a real line in which R and G are negligibly small.

Each section of an artificial line is composed of an inductance L and capacitor C connected in the form of an L-section low-pass filter, as shown in Figure 27. Since the characteristic impedance of a line is equal to the impedance of each elementary section, the characteristic impedance Z_o of the artificial line of Figure 26 is given by:

$$Z_o = \sqrt{\frac{L}{C}}$$

when L is the inductance and C the capacitance of each elementary section.

The delay time t_d required for a signal impulse to travel from one end of the line to the other may be calculated from:

$$t_d = N\sqrt{L \times C}$$

where N = the number of LC sections and L and C again are the inductance and capacitance of the section.

However, as described in an earlier lesson on filters, the network of Figure 26 also operates as a multi-section low-pass filter. The cut-off frequency f_c is given by:

$$f_c = \frac{1}{\pi\sqrt{LC}}.$$

Thus, all signal frequencies below f_c are transmitted with practically no loss in the line, but all above f_c are sharply attenuated.

Practical delay lines take two forms: the artificial line made up of lumped L and C sections as in Figure 26, and the "smooth" type in which the inductance is provided by a single continuous winding covered by a dielectric coating and an outer metal cover to provide the capacitance. The construction of the smooth line is shown in simple pictorial form in Figure 28A, and its diagrammatic representation in Figure 28B.

A second type of smooth delay line is illustrated in Figure 29. This arrangement is called a balanced line and consists of two windings wound in opposite directions and insulated by a dielectric. Thus part of the inductance is in each side of the circuit, and the capacitance exists between the two insulated windings. For a given delay time, this type of line has about one-half the d-c resistance of a single sided line.

When commercial delay lines are employed, a type having the desired characteristic impedance is selected, and the required delay time obtained by using as many units as necessary.

TRANSMISSION LINE CONSTRUCTION

Although only two basic types of transmission lines have been mentioned, there are several versions of these in frequent use. Illustrated in Figure 30, those particularly adapted to the transfer of r-f signals from antenna to the receiver are designated as follows:

(A) Twisted pair

(B) Twin Lead (Two-wire parallel conductor)

(C) Tubular Twin Lead

(D) Concentric or coaxial line

(E) Shielded pair

As shown in Figure 30A, the twisted pair consists of two insulated wires, the characteristic impedance of which ranges from 40 to 150 ohms. A feature of this line is its flexibility and comparatively low cost, but it has the disadvantage of a relatively high attenuation loss of 6.5 db per hundred feet at 50 mc. Since its losses become appreciably greater at higher frequencies, this type of line is rarely used in television installations.

The lines most commonly employed with television receiving antennas are the two-wire lines of Figure 30B and 30C. Known as "twin-lead," they have characteristics of low loss and flexibility with impedances ranging from 75 to 300 ohms. The flat type of Figure 30B has an attenuation of .85 db per hundred feet at 50 mc, and a maximum recommended length of 150 feet. When the capacitance between each conductor and ground is uniform along its entire length, the line is said to be "balanced" to ground. The lines of Figures 30B and 30C are balanced types. However, to maintain the balanced condition, they must be kept well clear of any conducting objects, such as guy wires, gutters, and down spouts.

The tubular twin lead of Figure 30C is a definite improvement over that of Figure 30B. As shown in Figure 30F, due to the hollow construction, power losses are reduced by keeping the moisture and dirt which gather on the line surface out of the strong field which exists between the two conductors. This difference is especially important at UHF frequencies. For instance, moisture on ordinary twin lead increases the loss by 23 db per hundred feet at 700 mc while tubular twin lead has an added loss of only 5 db.

Consisting of an insulated center wire enclosed by a concentric metallic outer covering which may be rigid or flexible, the concentric, or coaxial line is shown in Figure 30D. It is not subject to pickup of stray fields and is the most efficient of the four for VHF reception.

The shielded pair of Figure 30E consists of two separate parellel conductors insulated from each other by a low loss dielectric, such as the plastic polyethylene. The actual conductors are contained within a tubing made of copper braid which acts as a shield, and the entire assembly is covered with a rubber or plastic composition to provide weatherproofing.

This type has two outstanding advantages; first, the conductors are shielded against stray pickup and interference, and second, due to the enclosing shield, the line is balanced to ground at all points. Therefore, it can be run close to conducting objects without upsetting the line balance.

* * *

IMPORTANT DEFINITIONS

CHARACTERISTIC IMPEDANCE—(Z_0) The impedance which a transmission line has due to its distributed properties of inductance, capacitance, and resistance.

DELAY LINE—A section of real or artificial transmission line, the purpose of which is to delay a given signal by some desired interval of time (t_d).

STANDING WAVES—Stationary waves formed on a transmission line due to the addition of the incident and reflected waves.

STANDING WAVE RATIO—(SWR)—Ratio of peak to minimum voltages along a mismatched line.

SURGE IMPEDANCE—See characteristic impedance.

TRANSMISSION LINE—A set of conductors employed to transmit signal energy or current from one point to another.

STUDENT NOTES

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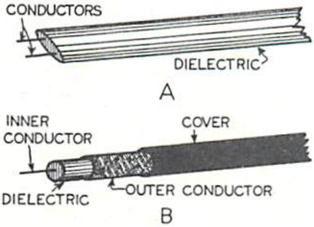

FIGURE 1

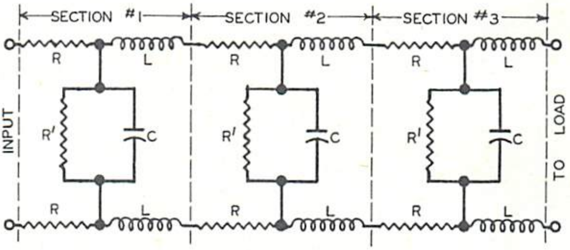

FIGURE 2

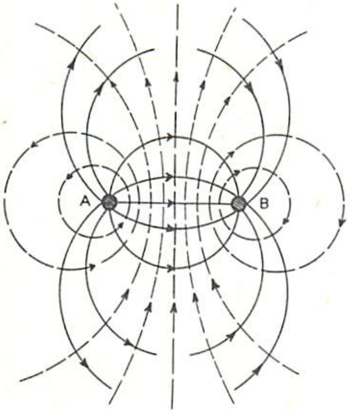

FIGURE 3

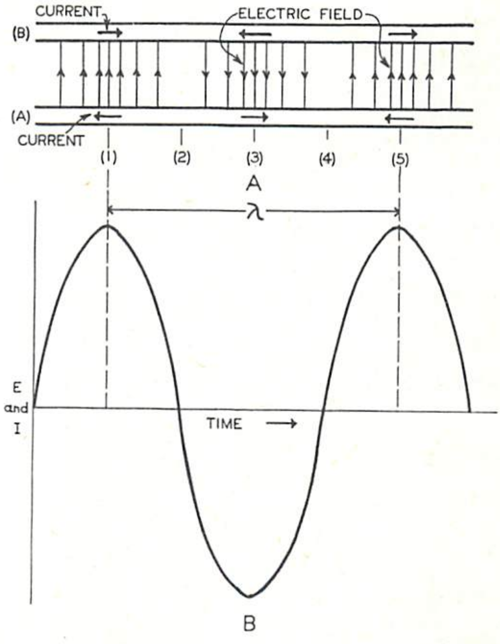

FIGURE 4

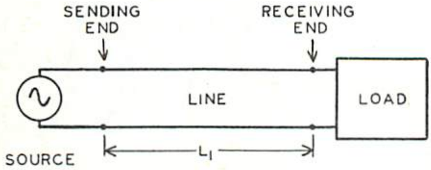

FIGURE 5

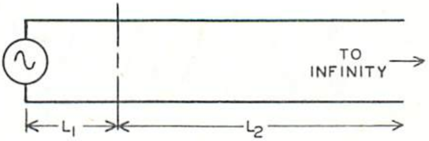

FIGURE 6

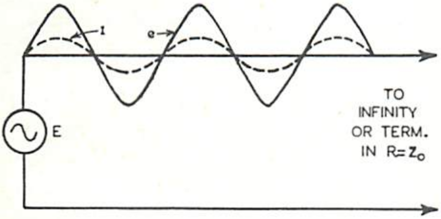

FIGURE 7

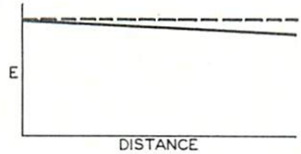

FIGURE 8

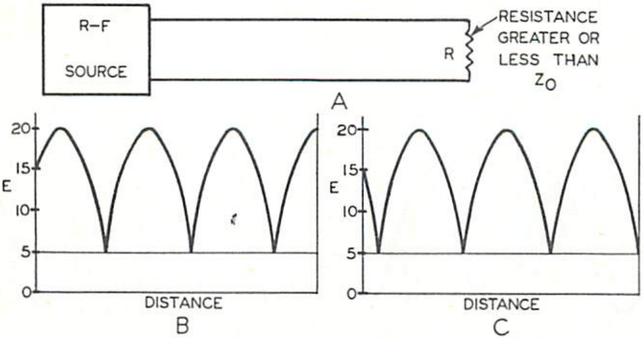

FIGURE 9

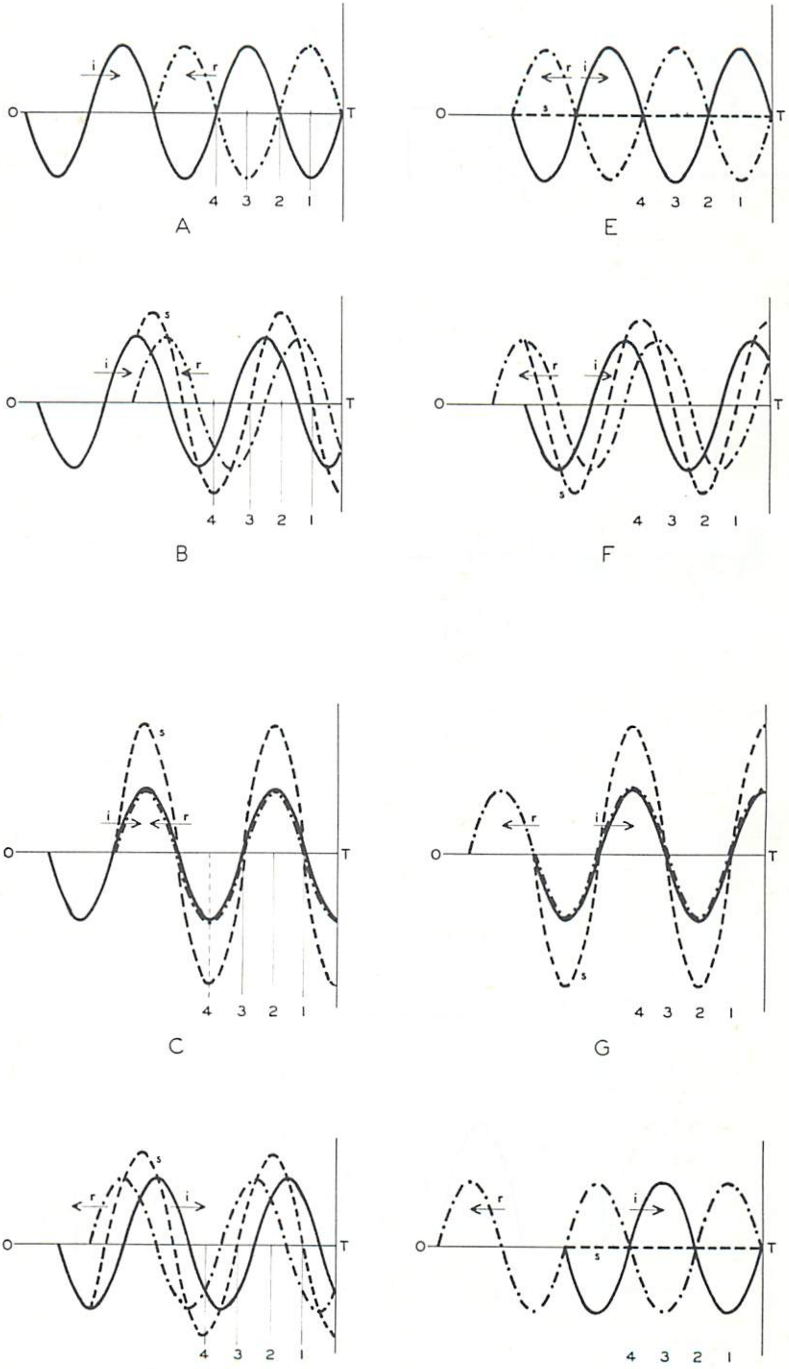
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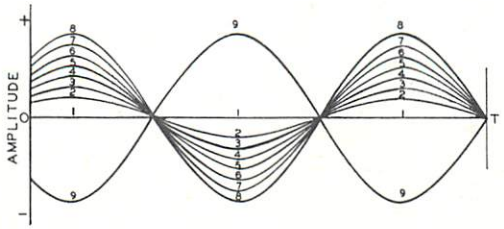
FIGURE 10



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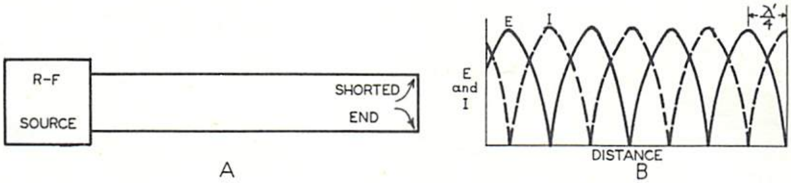

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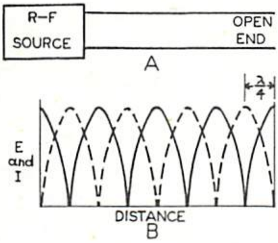

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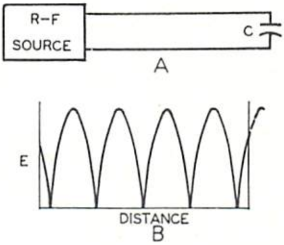

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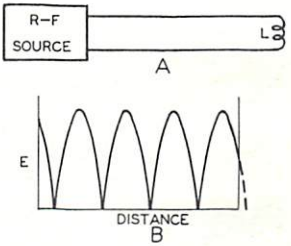

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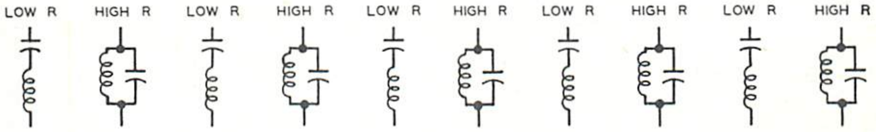

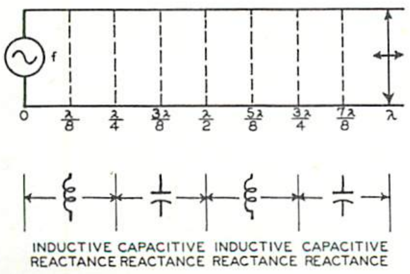

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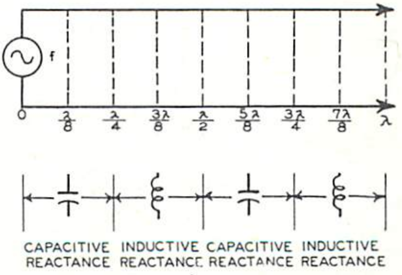
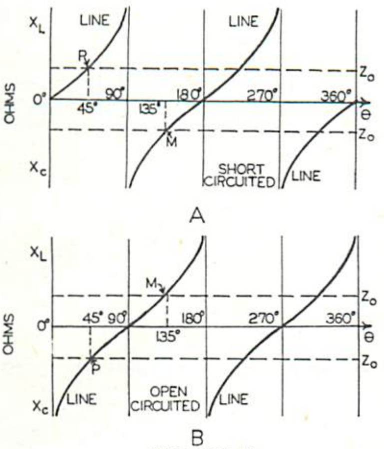


FIGURE 17



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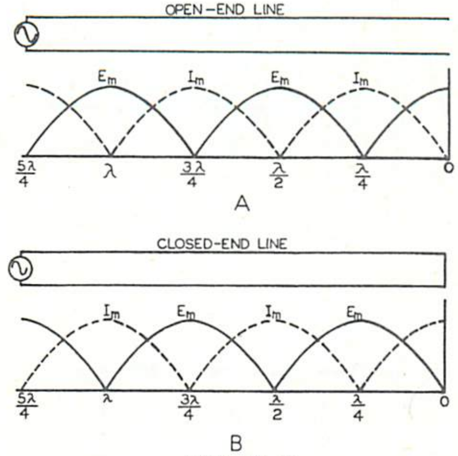


FIGURE 19

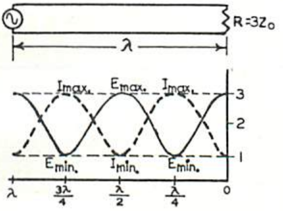
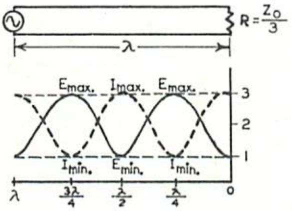


FIGURE 20



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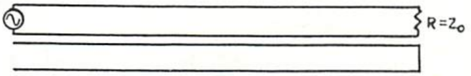

FIGURE 22

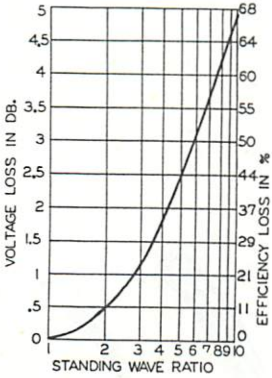

FIGURE 23

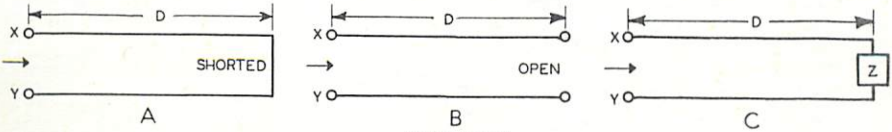

FIGURE 24

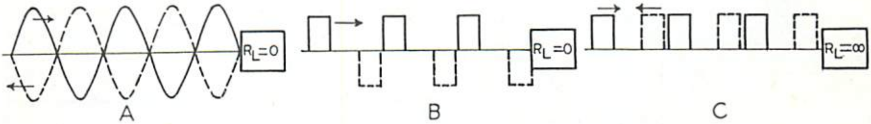

FIGURE 25

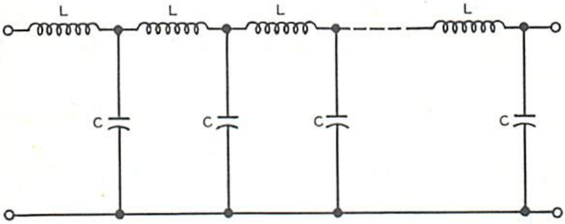

FIGURE 26

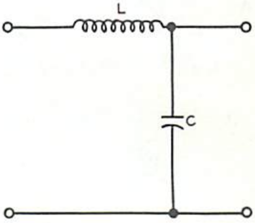

FIGURE 27

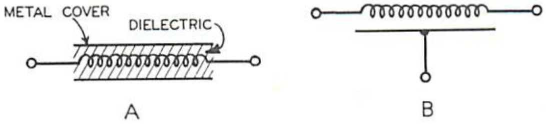

FIGURE 28

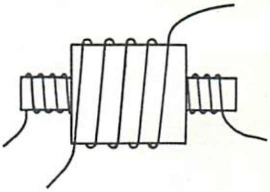

FIGURE 29

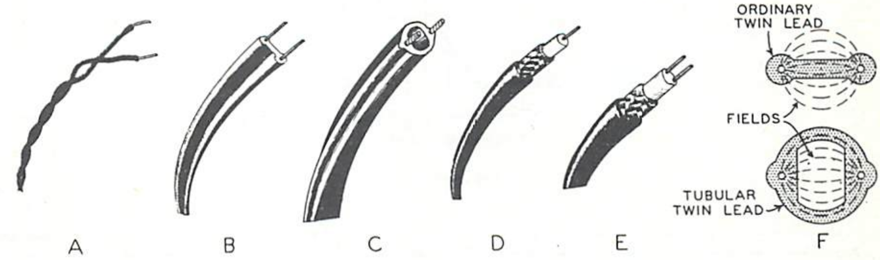

FIGURE 30

FROM OUR *Director's* NOTEBOOK

THE TEST OF A MAN

There's little satisfaction to be gained from
doing things
That hold no difficulties; it's the tough old
task that brings
Keen sense of worth and power to the man
who wins the fight;
His failures test his courage and his problems
prove his might:
Until a man has conquered loss and over-
come defeat,
He cannot fully understand just why success
is sweet.
I'm thankful for my disappointments, for
the battles lost,
And for mistakes that seemed to charge an
overwhelming cost;
I'm thankful for the days of doubt when it
was hard to see
That all things work together for the good
that is to be;
I'm glad for all that life has brought, be-
cause today I know
That men must brave adversities if they
would greater grow.

—O. Lawrence Hawthorne.

Yours for success,

W. C. De Vry

DIRECTOR

PRINTED IN U.S.A.